NOAA GAPP GRANTS GC01-101A AND GC01-101B: YEAR 2 PROGRESS REPORT

Title: *An Investigation of Persistence in the Coupled Land-Atmosphere System: The Role of Soil Moisture*

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ORIGINAL PROPOSAL ABSTRACT

A major focus of GAPP is improving our ability to predict hydrologic quantities such as evaporation, precipitation, and runoff at monthly, seasonal, and interannual timescales, and at spatial scales from continental to that of a local watershed. Persistence of anomalies in land-surface and atmospheric variables over such timescales is recognized as a possible aid to improving this predictability. Feedbacks between the land-surface and the atmosphere, such as local recycling of precipitation, are thought to enhance persistence in both surface and atmospheric variables, and a better understanding of how, when, where, and at what scales these feedback mechanisms operate is necessary for achieving desired predictability goals.

In particular, mesoscale atmospheric circulations forced by subgrid-scale (to a GCM) heterogeneity in the underlying landscape may play a potentially significant role in how precipitation recycling operates in a given region. The interactions between heterogeneity in soil moisture, the induced mesoscale circulations, and the corresponding impact of the resulting clouds and precipitation on the surface energy and water balance, introduce the potential for complex, nonlinear feedbacks between the surface and the atmosphere. These feedbacks may provide a mechanism for lengthening the timescale of mesoscale land-atmosphere interaction, thus perhaps significantly influencing large-scale precipitation and soil moisture over time. How this mechanism operates in the real climate system, and how the effects would vary between regions that are climatologically very different, such as the continental U.S. and Amazonia, is not known.

The objectives of the project proposed here are: (i) to investigate seasonal-scale persistence of anomalies in soil moisture and related variables, globally, though with a focus on the GAPP U.S. study area and the LBA Amazonian study area, using a sophisticated atmosphere/land/hydrology model; (ii) to uncover persistence mechanisms resulting from specific physical-dynamical processes and feedbacks in the coupled land-atmosphere system; (iii) to investigate the impact of subgrid-scale landscape heterogeneity in the GAPP and LBA study areas on large-scale precipitation recycling, the evolution of the soil moisture distribution over time, and large-scale persistence. This research is expected to address key aspects of the GAPP objectives, related to improving extended-range hydrologic predictability, as identified in the GAPP Science Plan.

ACCOMPLISHMENTS THROUGH YEAR 2

Long memory contained in anomalies of the land surface state, combined with the potential for a strong influence on variables like precipitation, means that improving our understanding of land-atmosphere coupling processes is probably one of the keys to improving long-term (seasonal-to-interannual) hydrometeorological predictability. In particular, feedbacks between soil moisture and convective rainfall are thought to contribute significantly to persistence in both variables. These feedbacks may be local, operating at relatively small scales, or they may result from larger-scale links, e.g., involving atmospheric circulation patterns.

A serious challenge for improving our understanding in this area is the bridging of scale gaps in space and time. There is growing evidence that surface variability at scales of 10s of km and less significantly impacts convective processes and precipitation on diurnal timescales. One mechanism is the forcing of lower-tropospheric mesoscale circulations. We wish to determine how this scale of land-atmosphere interaction affects persistence and hydrometeorology at much longer timescales and much larger spatial scales.

We are now in Year 2 of the project timeline. We have made substantial progress in the following areas necessary for successfully addressing the project's scientific questions: (i) the influence of initial soil moisture spatial variability on future precipitation; (ii) the characteristics and dynamics of landscape-forced mesoscale circulations; (iii) the two-way coupling between large-scale (synoptic) dynamics and mesoscale diurnal land-atmosphere interactions; (iv) the development of improved methodologies and tools for simultaneously investigating the important small-scale and large-scale processes and the interactions between them. So far the research conducted under this grant has contributed, wholly or in part, to 5 peer-reviewed publications (in various stages of the publication process), 3 additional papers in preparation for peer review, and a number of presentations (and abstracts). A listing appears near the end of this report.

We now briefly summarize the main accomplishments to date and the remaining tasks.

1. Coupling Between Large-Scale Atmospheric Processes and Mesoscale Land-Atmosphere Interactions

This work is aimed at examining the role of mesoscale land-atmosphere interactions—both their control by larger-scale meteorological conditions and their aggregate impact at these larger scales—in the coupled land-atmosphere system. The strategy is to use regional model simulations with relatively high spatial resolution (in order to capture relevant mesoscale processes) and run for relatively long timescales for this resolution (in order to capture interactions between diurnal mesoscale processes and synoptically-driven larger-scale processes, and to quantify their relative effects, over longer timescales). The premise is that land-atmosphere coupling is nonlinear, not only because of nonlinearities inherent in the individual components of the system (e.g., evapotranspiration from a vegetated surface, cloud and rain formation, etc.), or because of feedbacks between these components at a given scale, but also because of feedbacks between scales. Therefore, improved understanding of the land-atmosphere interactions and feedbacks that play such an important role in continental-scale hydrometeorology and hydrologic persistence should come, at least in part, from bridging scale gaps in space and time, as noted above. By "small-scale" or "mesoscale" we mean approximately 10-100 km, and by "large-scale" we mean 100s of km and greater.

Our focus is on the evolving rainfall and land-surface state, particularly soil moisture, and on the mesoscale atmospheric dynamics. The main region of interest is the U.S. southern Great Plains (SGP), primarily during the warm season, though we are also investigating similar questions as applied to Amazonia (see below). The following are the primary research questions motivating this portion of the project:

- How does the time-varying large-scale dynamics, along with associated precipitating systems, scale down to influence mesoscale land-surface heterogeneity and mesoscale atmospheric dynamical and thermodynamical processes, on timescales from sub-diurnal to monthly?
- How do these mesoscale effects scale up to potentially influence the larger-scale hydrometeorology, and how important is their aggregate impact over the domain on monthly timescales?
- What is the potential for feedbacks between the large-scale and mesoscale processes?

Specifically, we attempt to characterize the different mesoscale atmospheric responses to land-surface spatial variability under different large-scale synoptic and hydrologic conditions. For this purpose, we use high-resolution (2.5-km horizontal grid spacing) Regional Atmospheric Modeling System (RAMS) simulations over a domain the equivalent of a GCM grid cell (200 x 200 km^2). This domain coincides with the ARM/CART site in OK/KS. We extend the duration of each of these simulations out to a month, well beyond the diurnal timescale of the mesoscale land-atmosphere interactions of interest, to investigate the modulation of these processes by the time-varying, large-scale atmospheric environment. We explore the mesoscale atmospheric dynamical response to evolving land-surface spatial heterogeneity and large-scale synoptic and hydrologic conditions for July 1995, July 1996, and July 1997.

The results show that landscape-forced mesoscale dynamical activity in this domain is strongly controlled by the synoptic dynamical regime, i.e., the several-day-long, alternating wet and dry periods during each month. Landscape-forced mesoscale circulations occur ubiquitously during the dry periods as a result of the surface forcing (i.e., clear-sky conditions and hence strong surface fluxes). In addition, given the background atmospheric conditions, the vertical motions associated with convergence between individual circulation cells can directly produce either dry convection only, shallow moist convection, or deep convection.

Furthermore, the mesoscale flow carries out vertical transports with a characteristic domain-average magnitude and vertical structure. While the mesoscale transport has an inherently diurnal timescale, its aggregate impact over multiple days on the domain-average, vertical atmospheric thermodynamic structure is significant when compared to the large-scale-mean flow. Specifically, during the dry periods that make up a large fraction of each month, the mesoscale vertical moisture transport partially compensates for the effects of large-scale-mean subsidence on the water vapor profile by transporting boundary layer moisture up into the layer at about 2-4-km altitude. This mesoscale transport is a more efficient conduit between the boundary layer (BL) and the free troposphere than the smaller-scale turbulent fluxes, because it peaks in the middle and upper BL rather than near the surface, and because it penetrates much higher in the atmosphere. Composited over the dry periods, the mesoscale moisture transport is significant, approximately 20% of the large-scale transport in the lower and lower-mid-troposphere and opposite in sign for all three simulated months. This mesoscale opposition to the large-scale-mean vertical flux has the potential to influence subsequent convection and precipitation in the domain. By transporting moisture out of the BL, these vertical mesoscale circulations seem to effectively consume some of the low-level convective instability that could otherwise accumulate more strongly under the influence of the large-scale dynamics alone. This gradual consumption of instability therefore potentially limits the intensity of future large-scale convection and rainfall, thereby potentially altering the large-scale soil moisture-rainfall feedback.

These findings are summarized in a paper (Weaver 2003) submitted to *Journal of Hydrometeorology*. Note that the editor has suggested reorganizing the material into a separate Part I and II, so it is likely that this work will eventually appear as two papers.

We have also carried out a similar suite of high-resolution, month-long simulations over Rondonia, Brazil, motivated by similar questions. Here, however, we investigated one dry-season month, August 1996, and conducted experiments with different imposed deforestation patterns ranging from highly fragmented to highly clumped (though all with the same mean amount of deforestation). The major conclusions are the following. First, the degree of forest fragmentation affects the intensity and organization of landscape-forced mesoscale circulations. This altered mesoscale dynamics impacts vertical moisture transport, producing stronger shallow convection for a more highly clumped deforestation pattern. The enhanced vertical transport associated with this enhanced shallow convection dries the BL and moistens the lower free troposphere, thus decreasing the moist static instability progressively over several days. The net result is that subsequent deep convection is weaker and produces less rainfall. Over the course of the whole month, this reduction is significant, showing again that the diurnal mesoscale processes can scale up to longer timescales and larger spatial scales. These findings were presented at the 2003 AMS Annual Meeting and are being prepared for publication (Baidya Roy et al. 2003a).

Finally, we have done some additional work to examine in more detail the dynamics of these landscape-forced mesoscale circulations. Specifically, we used spectral analysis techniques to investigate the relationship between the characteristic horizontal spatial scale of simulated mesoscale circulations and the characteristic scale of the landscape heterogeneity that forces them. The simulations examined were also for the U.S. SGP and Rondonia. For both sets of cases, the organized mesoscale circulations were confined within a preferred lengthscale range of 10-20 km, significantly different from the dominant surface lengthscale in both regions. We concluded that even though the multiscale landscape patchiness tends to force the atmosphere over a wide range of scales, the land-atmosphere interaction process acts as a medium-pass filter to select intermediate-scale circulations. These insights into the relationship between mesoscale surface forcing and mesoscale atmospheric dynamical response should be useful for improving model subgrid parameterizations. These findings are summarized in a paper that has just been accepted for the upcoming GCIP special issue in the *Journal of Geophysical Research—Atmospheres* (Baidya Roy et al. 2003b).

2. Soil Moisture-Rainfall Feedbacks and Persistence of Large-Scale Soil Moisture Anomalies

The second major component of this project is the investigation of the interactions between soil moisture and precipitation at larger scales (up to global) and influence of these interactions on the persistence of soil moisture anomalies at these scales.

As a first step, we investigated the sensitivity of precipitation over the Mississippi River Basin and surrounding areas to both the spatial distribution of initial soil moisture and initial soil moisture amount. We carried out RAMS simulations (with a 40-km horizontal grid spacing) to determine the sensitivity of summertime precipitation during 1995, 1996, and 1997 to six different initial soil moisture patterns: three (control, dry, and wet) with a realistic spatial distribution, and three (control, dry, and wet) with a horizontally homogeneous distribution. In general, the impact of changing the spatial distribution of initial soil moisture (i.e., homogeneous vs. realistic) was most pronounced in the dry experiments and weakened nonlinearly with increasing domain-average initial soil moisture. In the dry regime, the impact of imposing a homogeneous soil moisture distribution was to enhance the total monthly precipitation in both the western half of the domain, where soil moisture was increased, and the eastern half of the domain, where soil moisture was decreased. These changes in precipitation in the runs with a homogeneous compared to realistic initial soil moisture spatial pattern resulted from enhanced evaporation in the western half of the model domain accompanied by enhanced west-to-east horizontal atmospheric moisture transport that helped restore the initially depleted soil moisture in the east. In this manner, the zonal moisture flux acted to re-establish the initial climatological soil moisture pattern of the region, thus acting as a negative feedback mechanism. In addition, meridional moisture transport into the simulation domain from the south decreased in the homogeneous compared to realistic initial soil moisture run through a decrease in the low-level meridional wind speed. Local precipitation recycling also played a role.

Longer simulations with a similar experiment design yielded insights into the characteristic persistence of this particular class of soil moisture anomaly: i.e., a "wet west, dry east" pattern. The coupling between local evaporation, atmospheric circulation changes, and convective precipitation produce a damping timescale of approximately three months for both the soil moisture anomaly pattern and the associated precipitation changes. These and the above findings are reported in a paper that has just been accepted into the GCIP special issue of the *Journal of Geophysical Research—Atmospheres* (Georgescu et al. 2003).

The next step is to build on these results and examine persistence and soil moisture-rainfall feedbacks in a multi-year, global modeling context. This component of the project is ongoing. We are currently analyzing a suite of multi-decadal runs conducted using the new NOAA/GFDL Flexible Modeling System (FMS) GCM. This analysis includes calculating the one-month-lag autocorrelation coefficients and anomaly persistence timescales for land-surface and atmospheric variables (e.g., soil moisture, soil temperature, and precipitation, among others). Our goal is two-fold. First, we wish to increase our understanding of the fundamental controls on soil moisture persistence, including the specific character of soil moisture-rainfall feedbacks, in target regions (e.g., the continental U.S. and Amazonia). Second, we wish to identify the aspects of these fundamental controls on persistence that might be most sensitive to the much smaller-scale (i.e., mesoscale), shorter-timescale land-atmosphere coupling processes discussed in the previous section of this report. These goals will be accomplished through sensitivity experiments with modified parameterizations of the land-surface and atmospheric processes (especially BL and convective processes) and comparisons with observations. In addition, we will use FMS global output to drive higher-resolution, limited-domain RAMS simulations and compare the results with those from the FMS alone over the same regions.

The recent inclusion of the GFDL model in this project is expected to be advantageous in a number of ways. Comparing results from this model with RAMS simulations and observations will provide useful information for the GFDL model development teams, and having access to a sophisticated global modeling system will enhance our current project. In addition, improving our understanding of this emerging model, its performance and characteristics, in the context of GAPP-relevant science questions, will help make it a more valuable tool for future investigations of interest to GAPP.

The other development relevant for the global modeling efforts and global-regional-mesoscale interaction studies required for this project is the near-completion of the Ocean Land Atmosphere Model (OLAM). OLAM is the highly improved extension of RAMS to a global modeling framework. OLAM is a new model with regard to its dynamic core, grid and memory structure, and numerical solution technique, but it adopts many of the well established methods that were developed in RAMS, and it shares the same physical parameterizations for microphysics, land-surface processes, radiative transfer, and subgrid cumulus convection. The atmosphere and land components of OLAM are currently in place and are undergoing extensive testing. An ocean component will eventually be added, but it is not immediately critical for the work in this project. OLAM has been designed specifically for studying the interaction between global and regional climate, so its contribution to the research questions discussed here is expected to be substantial.

The major improvements of OLAM relevant for this project include the following: (i) in RAMS, the volume occupied by a nested grid is covered by both fine grid and coarse grid cells, and prognostic calculations are performed on both grids, while in OLAM, any “nested” grid is simply a higher-resolution region of the overall grid structure; (ii) any of the assumptions commonly used in limited-area models and therefore also in RAMS that do not adhere to exact conservation of mass, momentum, and internal energy have been eliminated, rendering OLAM capable of runs spanning long timescales (e.g., multi-year and beyond); (iii) the vertical coordinate in OLAM is Cartesian, instead of terrain-following as in RAMS. Topography is represented using a variation of the "shaved grid cell" approach, which we call the “ADaptive Aperture” (ADAP) method. This approach is built upon a finite volume discretization of the conservation laws in which grid cell volumes and surface areas are explicitly represented. Surface areas are reduced or completely closed in order to prevent flux across the grid cell face wherever topography or other physical obstructions exist. The ADAP method allows a much more accurate representation of flow (and fluxes) in regions of complex terrain, around obstructions, and through vegetation canopies.

The bulk of the OLAM development work is supported by other sources than this grant. However, we are leveraging it to attack the scientific questions that form the core of this project. When testing is completed, the experiments with the GFDL FMS (alone and as used to drive RAMS) will be repeated with OLAM and the results compared. Particular attention will be paid to the combined global/regional capabilities of the model enabled by the improved grid-nesting procedure. In effect, OLAM can function as a full GCM with an embedded regional model, but with both models sharing identical dynamical and physical frameworks and code structure and with a seamless transition between grid boundaries. As such, it will allow us to take the final step required for this project to merge the larger-scale and smaller-scale components of this research and evaluate the impact of the coupling between the two on soil moisture-rainfall feedbacks and persistence.

Two publications describing OLAM and its preliminary results are in preparation for *Environmental Fluid Mechanics* (Walko and Avissar 2003a;b). In addition, two recent presentations on OLAM are also listed below.

Peer-Reviewed Publications Resulting from this Grant (Wholly or Partially Supported)

Baidya Roy, S., C.P. Weaver, and S.W. Pacala, 2003a: Forest fragmentation and its influence on convective rainfall in Rondonia. In preparation.

Baidya Roy, S., C.P. Weaver, D.S. Nolan, and R. Avissar, 2003b: A preferred dynamical scale for landscape-forced mesoscale circulations? *J. Geophys. Res,* accepted.

Georgescu, M., C.P. Weaver, R. Avissar, R.L. Walko, and G. Miguez-Macho, 2003: Sensitivity of model-simulated summertime precipitation over the Mississippi River basin to the spatial distribution of initial soil moisture. *J. Geophys. Res.,* accepted.

Walko, R.L., and R. Avissar, 2003a: OLAM: Extension of RAMS to global modeling applications. Part I: Model description and ADAP experiments. *Environ. Fluid Mech.,* in preparation.

Walko, R.L., and R. Avissar, 2003b: OLAM: Extension of RAMS to global modeling applications. Part II: Numerical simulation test results. *Environ. Fluid Mech.,* in preparation.

Weaver, C.P., 2003: Coupling between large-scale atmospheric processes and mesoscale land-atmosphere interactions in the U.S. southern Great Plains during summer. Part I: Diurnal perspective. *J. Hydrometeorology,* submitted.

Weaver, C.P., S. Baidya Roy, and R. Avissar, 2002: Sensitivity of simulated mesoscale atmospheric circulations resulting from landscape heterogeneity to aspects of model configuration. *J. Geophys. Res.* **107**, pp. LBA 8-1 to LBA 8-21, DOI:10.1029/2001JD000376.

Weaver, C.P., and R. Avissar, 2002: Reply to 'Comments on "Atmospheric disturbances caused by human modification of the landscape"' by J.C. Doran and S. Zhong. *Bull. Amer. Meteorol. Soc.* **83**, 280-283.

Presentations (Selected)

"Mesoscale land-atmosphere interactions: Control by larger-scale meteorology and upscaling impacts." Invited seminar at the NASA Goddard Institute for Space Studies, February 2003.

"The sensitivity of simulated central U.S. summer precipitation and atmospheric moisture budget to both the spatial distribution and the amount of initial soil moisture." Talk at the 17th Conference on Hydrology, 83rd AMS Annual Meeting, Long Beach, CA, February 2003.

"Impact of deforestation on precipitation." Talk at the 17th Conference on Hydrology/Symposium on Observing and Understanding the Variability of Water in Weather and Climate, 83rd AMS Annual Meeting, Long Beach, CA, February 2003.

"Design and progress report on OLAM, a global model cousin of RAMS." Invited seminar in the Department of Atmospheric Science, Colorado State University, January 2003.

"Development of OLAM." Talk at the 5th RAMS Users' Workshop, Santorini, Greece, October 2002.

"The co-evolution of the large-scale magnitude and mesoscale spatial heterogeneity of precipitation and soil moisture over the GCIP domain on monthly/seasonal timescales." Talk at the AMS/GAPP Mississippi River Climate and Hydrology Conference, New Orleans, LA, May 2002.

"A preferred dynamical scale for landscape-forced mesoscale circulations?" S. Baidya Roy, C.P. Weaver, D.S. Nolan, and R. Avissar. Poster at the AMS/GAPP Mississippi River Climate and Hydrology Conference, New Orleans, LA, May 2002.

"An estimate of the sensitivity of large-scale model simulations to the mosaic of tiles approach to land-atmosphere coupling: A case study over the GCIP region." L. Luo, C.P. Weaver, A. Robock, and R. Avissar. Poster at the AMS/GAPP Mississippi River Climate and Hydrology Conference, New Orleans, LA, May 2002.

"The impact of initial soil moisture amount and spatial distribution on the simulation of precipitation during the 1995, 1996, and 1997 GCIP ESOPs." M. Georgescu, C.P. Weaver, R. Avissar, and R.L. Walko. Poster at the AMS/GAPP Mississippi River Climate and Hydrology Conference, New Orleans, LA, May 2002.